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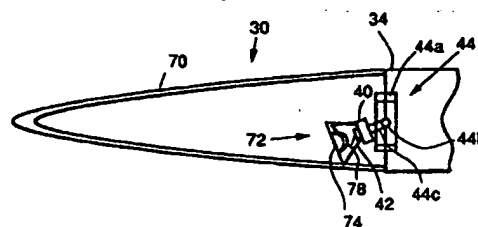
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(54) **Optical imaging system including generally conical, transparent protective dome and optically refractive fixed corrector for reversing conical deformation created by viewing through the dome.**

(57) A camera (40) is mounted on a gimbal (44) inside a missile (30) and views forwardly through a transparent, generally conical front-dome or ogive (70). An optically refractive corrector (72) is mounted in front of the camera lens (42) for integral movement therewith. The corrector (72) has a least one conical surface segment (74a,74b) which is dimensioned to reverse optical conical deformation created by the dome (70). The conical deformation includes little or no refractive power in a plane defined by the axis (38) of the dome (70) and the look axis (46) of the camera (40) and gimbal (44), and progressively varying one-dimensional refraction perpendicular to this plane. Variables including the apex angles (α_1, α_2) of cones (76,78) which define the surfaces (74a,74b), the angle (α_3) between the axes (76b,78b) of the cones (76,78), the distances (D1,D2) between the apices (76a,78a) of the cones (76,78) and the center (74c) of the corrector (72), the tilt angle (α_5) and the index of refraction of the corrector (72) provide sufficient degrees of freedom to enable a best fit solution which substantially reverses the conical deformation created by the dome (70).

FIG. 7.



BACKGROUND OF THE INVENTION

Field of the Invention

The present invention generally relates to the art of optical imaging systems, and more specifically to the correction of conical deformation created by a camera viewing through a transparent, generally conical dome or ogive.

Description of the Related Art

A rocket or missile is preferably provided with a streamlined nose cone or front dome to minimize aerodynamic drag and maximize the efficiency of its propulsion system. The dome is pointed at its front end, and is axi-symmetric in that its cross section in any plane perpendicular to its longitudinal axis is circular. The dome can be perfectly conical, or have a generally conical ogive shape with a gradually curved cross section in a plane passing through its longitudinal axis.

Cameras are carried by missiles for guidance, tracking and information gathering purposes. The camera must face generally forward for tracking a ground or airborne target. It is highly desirable to make the dome transparent and mount the camera on a gimbal inside the missile so that it can view forwardly through the dome at a variable angle. However, the dome creates optical aberrations which make objects viewed therethrough appear offset from their true positions.

A dome having an ogive shape such as defined by the well known Von Karman equations is desirable over a perfectly conical dome since it produces less drag. However, a curved dome such as a Von Karman ogive introduces an aberration known as "boresight error" such that a ray passing through the dome surface exits at an angle which is non-parallel to its entrance angle.

Boresight error can be eliminated by making the inner surface of the dome non-parallel to the outer surface as disclosed in copending U.S. patent application serial no. 07/764,273, filed Sept. 23, 1991, entitled "REFRACTION CORRECTION FOR AXISYMMETRIC VIEWING WINDOW", by K. Friedenthal.

A second type of aberration created by viewing through a conical or generally conical ogive dome is known as "conical deformation", and is generally astigmatic. For a perfectly conical dome, there is zero refractive power in a plane defined by the longitudinal axis of the dome and the gimbal look axis, and one-dimensional diverging power perpendicular to this plane. The power is theoretically infinite at the tip of the dome, and decreases progressively with distance from the tip. For a Von Karman or other ogive having a curved shape, there is also a relatively small amount of diverging power in the plane of the dome

and gimbal look axes.

The one-dimensional refraction created by a conical dome is comparable to that created by a cylindrical lens. For this reason, attempts have been made to eliminate conical deformation using cylindrical lenses. Although a portion of the deformation can be reversed (canceled or corrected) by a cylindrical lens, the refracting power of a dome is not constant with position as with a cylindrical lens, but increases toward the tip of the dome. For this reason, an unacceptable amount of residual conical deformation exists at all but a single viewing position on the dome, even if a best compromise cylinder power has been determined based on the geometry of the design.

SUMMARY OF THE INVENTION

In accordance with the present invention, a camera is mounted on a gimbal inside a missile and views forwardly through a transparent, generally conical front dome or ogive. An optically refractive corrector is mounted in front of the camera lens for integral movement therewith.

The corrector has a least one conical surface segment which is dimensioned to reverse optical conical deformation created by the camera viewing through the dome. The conical deformation of the dome includes little or no refractive power in a plane defined by the longitudinal axis of the dome and the gimbal look axis, and progressively varying one-dimensional diverging power perpendicular to this plane.

Conical deformation created by a perfectly conical dome can be reversed (canceled or corrected) by a corrector having a single convex surface and a flat surface, or opposite convex and concave surfaces. For an ogive with a curved Von Karman or other shape, the corrector can have convex and concave conical surfaces which are offset from each other to further correct for refractive power of the dome in the plane defined by the longitudinal axis of the dome and the gimbal look axis as well as in the plane perpendicular thereto.

Variables including the apex angles of the cones, the angle between the axes of the cones, the distances between the apices of the cones and the center of the corrector, the tilt angle and index of refraction of the corrector provide sufficient degrees of freedom to enable a best fit solution which substantially cancels the conical deformation created by the dome.

These and other features and advantages of the present invention will be apparent to those skilled in the art from the following detailed description, taken together with the accompanying drawings, in which like reference numerals refer to like parts.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram for describing the conical optical deformation created by viewing through a generally conical dome or ogive;

FIG. 2 is similar to FIG. 1, but illustrates a first corrector embodying the invention for reversing the conical deformation;

FIG. 3 is a side elevation illustrating the corrector of FIG. 2;

FIG. 4 is front elevation of the corrector;

FIG. 5 is a section taken on a line V-V of FIG. 3;

FIG. 6 is a section taken on a line VI-VI of FIG. 3;

FIG. 7 is similar to FIG. 2, but illustrates a second corrector embodying the invention;

FIG. 8 is a diagrammatic sectional view illustrating the design variables of the corrector of FIG. 7;

FIGs. 9 and 10 are sectional views illustrating third and fourth correctors embodying the invention;

FIG. 11 is a perspective view illustrating a method of forming a convex surface of the present corrector; and

FIG. 12 is similar to FIG. 11 but illustrates a method of forming a concave surface of the corrector.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates a transparent, generally conical front dome or ogive 10 for a rocket, missile or the like. For the purposes of the invention, the term "generally conical" encompasses shapes including a perfect cone 12 as indicated in broken line, and shapes such as the illustrated dome 10 which differ somewhat from the cone 12 but have pointed front ends and are axi-symmetric about a central longitudinal axis 14.

The outer surface of the dome 10 is preferably defined by the well known Von Karman equations, providing a much more streamlined shape and thereby lower aerodynamic drag than the cone 12. The inner surface of the dome 10 is preferably non-parallel to the outer surface thereof as disclosed in the above referenced copending application to Friedenthal to correct for "boresight error", such that a light ray passing through the dome 10 exits parallel to its entrance path.

It will be assumed that a scene forward and below the dome 10 is viewed along an axis 15 which intersects the axis 14 at a center 16 of the base of the dome 10. A three dimensional rectangular coordinate system includes a Z axis which coincides with the axis 15, and X and Y axes which extend perpendicular to the Z axis. In the illustrated case in which the Y and Z axes lie in the plane of the drawing, the X axis is perpendicular to the plane of the drawing.

The dome 10 creates conical deformation of light passing therethrough, and distortion of an image of a

scene viewed through the dome 10. It will be assumed that two sets of parallel light rays 17 and 18 pass through the dome 10 from left to right parallel to the axis 15, with the rays 17 being closer to the axis 14 than the rays 18. The rays 17 are laterally spaced from each other perpendicular to the plane of the drawing. The rays 18 are similar to the rays 17. The rays 17 and 18 are refracted by the dome 10 so as to diverge in planes which are parallel to the plane defined by the X and Z axes. In the illustrated case in which the Y and Z axes lie in the plane of the drawing, the divergence of the rays 17 and 18 occurs in planes which lie above and below the axis 15 respectively and extend perpendicular to the plane of the drawing.

However, the optical power of the dome 10 in the X-Y plane at a point 20 at which the rays 17 pass therethrough is greater than the optical power thereof at a point 22 at which the rays 18 pass through the dome 10. For this reason, the rays 17 are refracted more than the rays 18. The refractive power at a tip 24 of the dome 10 can be theoretically infinite, and decreases with distance from the tip 24.

The diverging refraction created by the dome 10 or 12 is known as "conical deformation", and is generally astigmatic in that in its pure form there is no refraction in one plane (the plane of the drawing in which the Y and Z axes lie) and one-dimensional refraction in an orthogonal plane (perpendicular to the plane of the drawing and coincident with or parallel to the X/Z plane). Although comparable to the one-dimensional refraction created by a cylindrical lens, conical deformation differs from cylinder refraction in that the lens power or amount of refraction varies with position along the surface of the dome, rather than being constant as is the case of a cylindrical lens.

For the case of the perfect cone 12, all of the divergence occurs in or parallel to the X/Z plane, and there is no divergence in the Y/Z plane. However, for the dome 10 which has a curved cross section in the Y/Z plane, there will be a relatively small amount of divergence in the Y/Z plane which depends on the curvature of the dome 10.

A missile 30 including an optical imaging system 32 embodying the present invention is illustrated in FIG. 2. The missile 30 includes a body 34 having a transparent dome 36 mounted on its front end. The dome 36 is axi-symmetric about a central longitudinal axis 38 and has a perfectly conical shape as illustrated at 12 in FIG. 1.

A camera 40 having an imaging lens 42 is mounted on a gimbal 44 inside the body 34 so as to view forwardly through the dome 36. The gimbal 44 is driven by a servo system (not shown) so as to track a target on the ground or in the air, and may have any desired number of degrees of freedom of movement. In the preferred embodiment, the gimbal 44 includes a cylindrical cage 44a which is rotatable about the axis 38 and supports a shaft 44b which spans a diameter of

the cage 44a and rotates integrally therewith. The camera 40 is mounted on an arm 44c which is rotatably supported by the shaft 44b.

With the gimbal 44 oriented in the position illustrated in FIG. 2, the shaft 44b extends parallel to the X axis (perpendicular to the plane of the drawing), and the camera 40 is rotatable or tiltable about the X axis. As shown, the camera 40 is tilted downwardly relative to the axis 38 by an angle θ . The gimbal 44 enables the camera 40 to cover the entire field of view forward of the dome 36 with 360° of freedom of rotation about the longitudinal axis 38, and up to 90° of freedom of rotation ($0 \leq \theta \leq 90^\circ$) about the axis of the shaft 44b. At any position of the gimbal 44, a look axis 46 of the gimbal 44 and camera lens 42 is coplanar with the axis 38 so that the conical deformation created by the dome 36 varies only in one dimension (with the angle θ).

In accordance with the present invention, a corrector 48 is mounted in front of the camera lens 42 for integral movement therewith. As better seen in FIGS. 3 to 6, the corrector 48 includes a body 50 formed of a transparent, optically refractive material. As illustrated in FIG. 4, the body 50 is preferably circular as viewed along the axis 46, although the invention is not so limited. The body 50 has a convex conical front surface 50a which faces the dome 36 and is defined by a cone 52, and a concave conical rear surface 50b which faces the camera 40 and is defined by a cone 54.

The cone 54 is smaller than and parallel to the cone 52 such that if the space between the cones 52 and 54 were filled with solid material, the cones 52 and 54 in combination would define a hollow cone 56 having a generally upwardly pointing (inclined above the axis 46) apex 56a, a central axis 56b, a base 56c and a wall 56d of uniform thickness. The body 50 constitutes a segment or portion of the cone 56, with the surfaces 50a and 50b being segments of the conical surfaces of the cones 52 and 54 respectively.

The body 50 has a center 50c which lies on the axis 46, and is oriented such that the axis 46 is normal to the convex surface 50a and also to the concave surface 50b at the center 50c. The center 50c is displaced from the apex 56a of the cone 56 by a decenter distance D. The cones 52, and 54 and 56 have a common apex angle α . The corrector 48 has a converging refracting power which reverses (cancels or corrects) the divergence created by the dome 36.

Referring again to FIG. 2, sets of light rays 60 and 62 which are similar to the rays 17 and 18 described with reference to FIG. 1 pass through the dome 36 parallel to, and above and below the axis 46 respectively. The rays 60 and 62 pass through the corrector 48 and are focussed by the camera lens 42 to form an optical image in the camera 40. The rays 60 are closer to the axis 38 of the dome 36 than are the rays 62, and are therefore subjected to a greater amount of conical

deformation and thereby diverging refraction than the rays 62.

However, the corrector 48 is dimensioned and oriented in such a manner as to reverse or correct the conical deformation created by the dome 36 such that the image of a scene viewed by the camera 40 through the dome 36 is of high resolution. More specifically, the optical power of the body 50 in the X-Y plane at a point 64 where the rays 60 pass through the body 50 is greater than the optical power of the body 50 at a point 66 where the rays 62 pass through the body 50. FIGS. 5 and 6 are cross sections through the points 64 and 66 respectively which illustrate the difference in optical power at the points 64 and 66.

The ray 60 is converged by the body 50 parallel to the X/Z plane by an amount which is substantially equal to the divergence created by the dome 36. The ray 62 is converged by the body 50 parallel to the X/Z plane by an amount which is substantially equal to the divergence created by the dome 36, with the amount of divergence and convergence being less than that of the ray 60. The thickness and index of refraction of the body 50, the apex angle α and decenter distance D are selected in accordance with the geometry of the dome 36 so as to create equal and opposite conical deformation which reverses that created by the dome 36 and produce a high resolution view through the dome 36.

The dome 36 illustrated in FIG. 2 is perfectly conical and creates optical aberration only in or parallel to the X/Z plane. The aberration is constituted by pure conical deformation, and can be reversed by the corrector body 50 which has a purely conical shape with uniform wall thickness. FIG. 7 illustrates a dome 70 in the shape of a curved ogive such as defined by the Von Karman equations and designated as 10 in FIG. 1. As discussed above, the dome 70 additionally creates divergence in the Y/Z plane which is smaller than the divergence in or parallel to the X/Z plane.

Although the resolution through the dome 70 can be greatly improved using the corrector 48, it can be improved yet further and/or the gimbal look angle can be increased by a corrector 72 which is illustrated in vertical cross section in FIG. 8. The corrector 72 has a body 74 which is defined by two offset cones 76 and 78 and highlighted by cross hatching in the drawing. The corrector 72 can thereby be referred to as a "double offset cone corrector". The cone 76 defines a convex conical front surface 74a which faces the dome 70, whereas the cone 78 defines a concave rear surface 74b which faces the camera 40. The thickness of the body 74 increases from the upper to the lower portion thereof.

The cone 76 has an apex 76a, a central axis 76b, and a wall 76c which defines the surface 74a of the corrector body 74. The cone 78 has an apex 78a, a central axis 78b, and a wall 78c which defines the surface 74b of the body 74. The cone 76 has an apex an-

gle α_1 which is illustrated as being larger than an apex angle α_2 of the cone 78. The axes 76b and 78b lie in the plane of the drawing, and extend at an angle α_3 relative to each other. The apices 76a and 78a point generally upwardly (inclined above the axis 46) at angles which differ from each other by less than 90°.

The body 74 has a center 74c through which the axis 46 passes. The apex 76a of the cone 76 is vertically spaced from the center 74c by a decenter distance D1 which is illustrated as being greater than a decenter distance D2 between the axis 78a of the cone 78 and the center 74c. A wedge angle α_4 is defined between the surfaces 74a and 74b of the body 74. A line 77 which is normal to the front surface 74a at the center 74c is tilted downwardly from the axis 46 by an angle α_5 . The front surface 74a is consequently tilted forward from the vertical by the angle α_5 .

Due to extensive interaction between variables, the dimensions of the correctors 48 and 72 are preferably determined by an optical analysis program which is commercially available for use with a general purpose computer. A representative program is marketed as "CodeV" by Optical Research Associates of Pasadena, CA. The procedure includes inputting the geometry of the dome 36 or 70, and individually varying the dimensions of the corrector 48 or 72 until a best fit compromise solution is obtained. The values to be optimized typically include standardized parameters such as root mean square (RMS) spot size and image quality expressed as amount of wavefront error.

The variables for the corrector 48 include the apex angle α , decenter distance D and the index of refraction and thickness of the body 50. The variables for the corrector 72 include the apex angles α_1 and α_2 and the angle α_3 between the axes 76b and 78b which in combination determine the wedge angle α_4 , the tilt angle α_5 , the decenter distances D1 and D2 and the index of refraction of the body 74. Generally, the index of refraction is made as large as practical to minimize the thickness of the corrector 48 or 72.

The conical deformation created by the dome 36 or 70 varies with the pitch or tilt angle θ of the camera 40 as described with reference to FIG. 2. More specifically, the deformation decreases as the angle θ increases. A fixed corrector will provide optimal correction of conical deformation only at a particular value of θ . The optical power of the dome 36 or 70 is so large at small values of θ that imaging at these angles is impractical. Therefore, the angle θ , within a predetermined usable range, is preferably included as a variable in computing the best fit compromise solution for the corrector geometry.

The large number of individually variable dimensions enable a best fit compromise solution which will reverse the conical deformation created by the dome 36 or 70 to enable substantially undistorted imaging

by the camera 40. In the case of the dome 70, the conically distorted wavefront is converted to a nominally spherical wavefront by the corrector 72 with negligible change in focus as a function of θ . Thus, the camera 40 can be of the fixed focus type.

However, if refocussing is necessary, it can be accomplished automatically if the camera 40 is provided with an autofocus mechanism. If not, the amount of refocus is a direct function of the angle θ , and can be predetermined and programmed into a focus servo drive (not shown) for the camera 40.

Whereas the correctors 48 and 72 have two opposite convex and concave surfaces, it is within the scope of the invention to configure a corrector as having any conical shape with converging refractive power. FIG. 9 illustrates, in horizontal cross section, a corrector 80 having a convex conical front surface 80a and a flat or planar rear surface 80b, whereas FIG. 10 illustrates a corrector 90 having convex conical front and rear surfaces 90a and 90b respectively.

A corrector embodying the present invention is preferably formed of a material such as germanium (Ge) or silicon (Si) which has a relatively high index of refraction and can be machined in a lathe using a diamond cutting tool. However, other materials such as gallium arsenide (GaAs), zinc sulfide (ZnS) or zinc selenide (ZnSe) which have high indices of refraction can be used for practicing the invention.

FIGs. 11 and 12 illustrate an exemplary method of fabricating the corrector 72 by diamond turning. In FIG. 11, a blank 100 made of silicon or the like is fixed to a jig 102 which is in turn mounted on a lathe chuck 104. The jig 102 has an outer surface in the shape of a cone with the same apex angle as the cone 76 which defines the convex front surface 74a of the corrector body 74. The blank 100 is rotated integrally with the chuck 104 and jig 102, and a diamond cutting tool 106 is moved via a feed arm 108 to cut or machine the exposed surface of the blank 100 into the shape of the cone 76.

Then, as illustrated in FIG. 12, a jig 110 having an inner surface in the shape of a cone with the same apex angle as the cone 78 which defines the concave rear surface 74b of the corrector body 74 is mounted on the chuck 104, and the blank 100 is fixed to the jig 110 with the unmachined surface exposed. The tool 106 is then moved by the feed arm 108 to cut the exposed surface of the blank 100 into the shape of the cone 78.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art, without departing from the spirit and scope of the invention. Accordingly, it is intended that the present invention not be limited solely to the specifically described illustrative embodiments. Various modifications are contemplated and can be made without departing from the spirit and

scope of the invention as defined by the appended claims.

Claims

1. A corrector for correcting optical conical deformation created by a transparent, generally conical dome, comprising a transparent, optically refractive body having at least one substantially conical surface for creating reverse conical deformation which is substantially the inverse of said conical deformation created by the dome. 5
2. A corrector as in claim 1, in which said at least one substantially conical surface comprises a first conical surface segment formed on one side of the body and a second conical surface segment formed on an opposite side of the body. 10
3. A corrector as in claim 2, in which said first and second conical surface segments have axes of revolution which lie in a plane. 15
4. An optical imaging system, comprising: 20
 - a transparent, generally conical dome which creates optical conical deformation when viewed there-
5. A system as in claim 4, in which: 25
 - the camera includes an imaging lens; and
 - the corrector is mounted in front of and integrally movable with the imaging lens relative to the dome. 30
6. A system as in claim 4, in which said at least one substantially conical surface comprises a first conical surface segment formed on one side of the body and a second conical surface segment formed on an opposite side of the body. 35
7. A system as in claim 6, in which said first and second conical surface segments have axes of revolution which lie in a plane. 40
8. A system as in claim 6, in which said first and second conical surface segments are decentered by different distances. 45
9. A system as in claim 4, in which: 50
 - said at least one substantially conical surface comprises a convex conical surface segment formed on one side of the body; and
 - the body has a flat surface on an opposite side thereof. 55
10. A missile, comprising:
 - a transparent, generally conical front

dome which creates optical conical deformation when viewed therethrough;

a camera mounted inside the dome for viewing therethrough; and

a corrector including a transparent, optically refractive body which is disposed between the camera and the dome and has at least one substantially conical surface for creating reverse conical deformation which is substantially the inverse of said conical deformation created by the camera viewing through the dome.

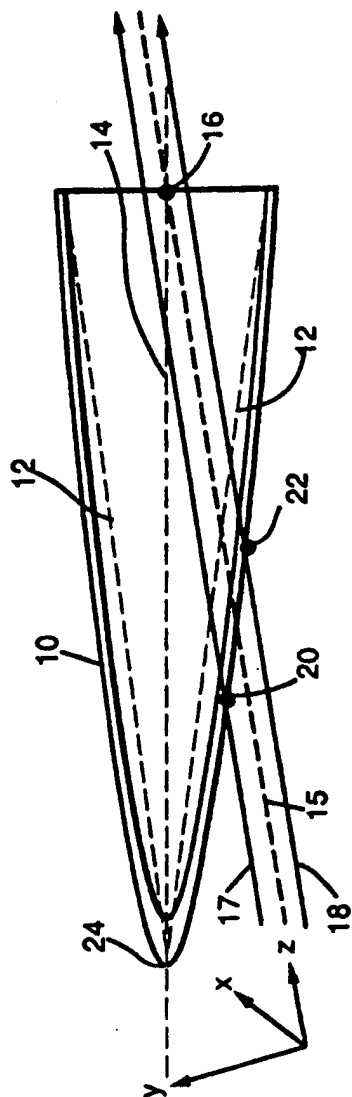
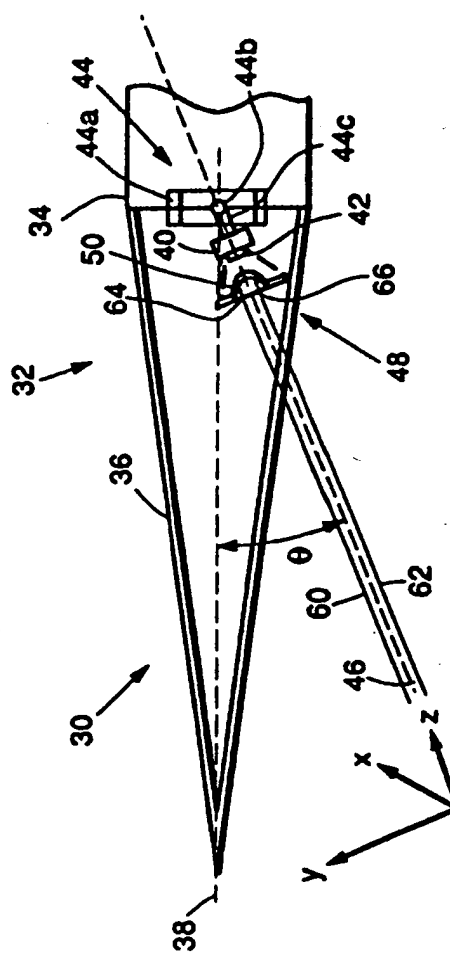


FIG. 1.

FIG. 2.



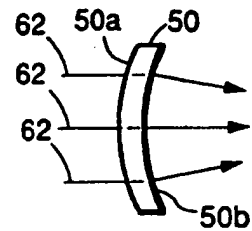
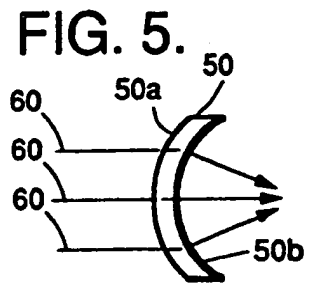
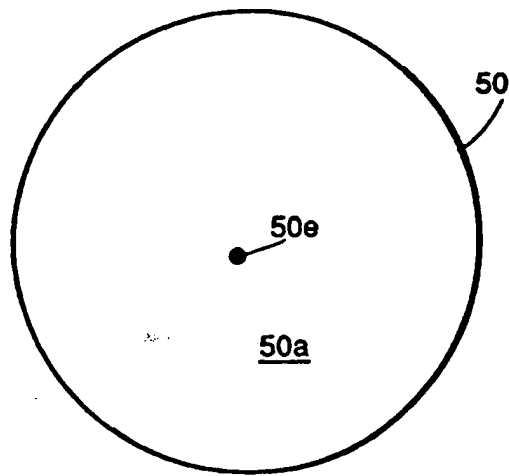
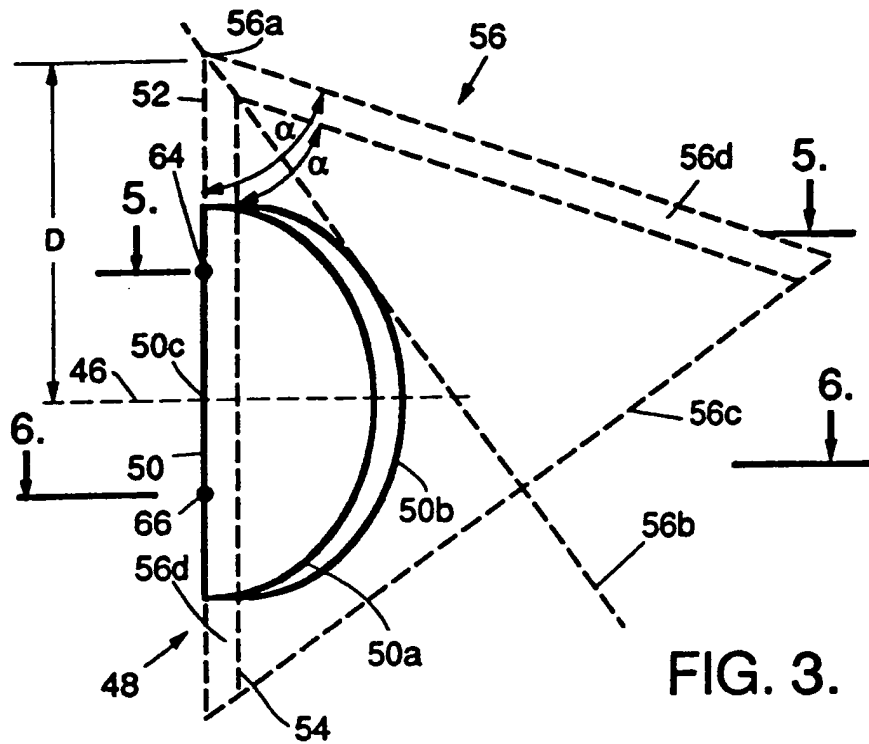


FIG. 7.

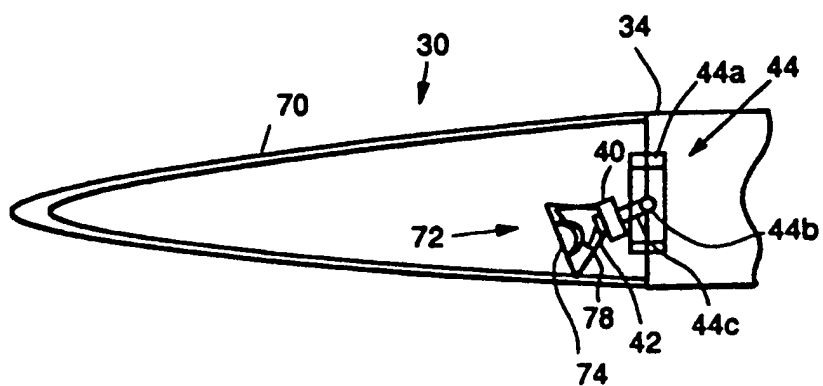
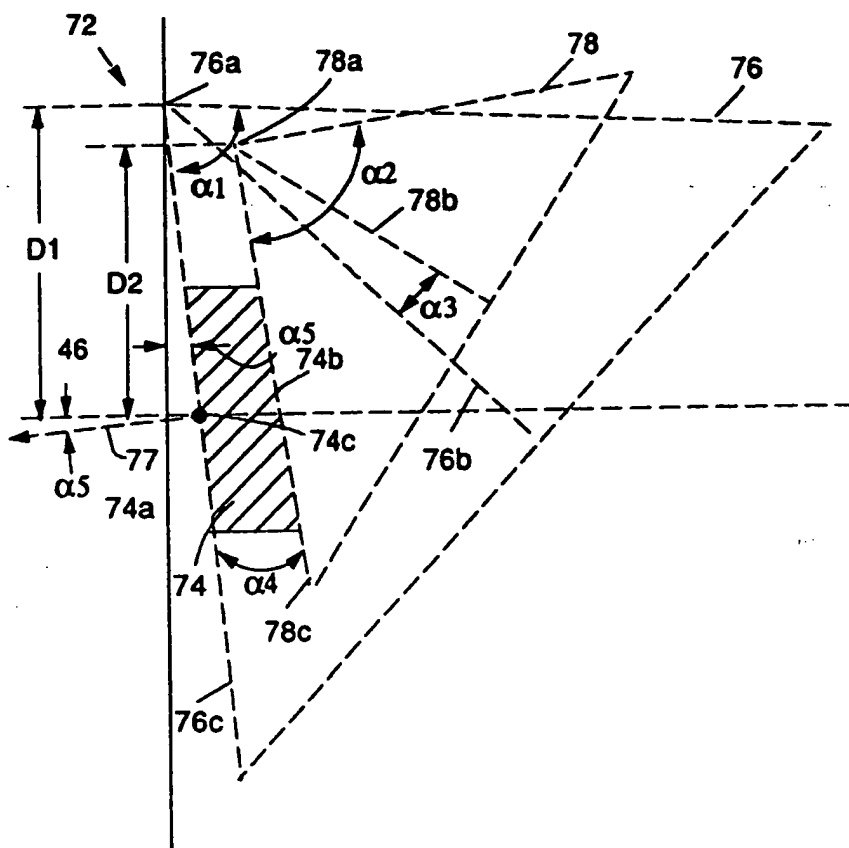


FIG. 8.



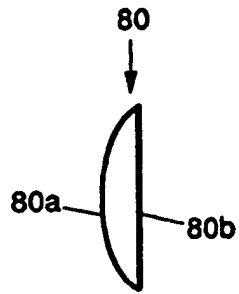


FIG. 9.

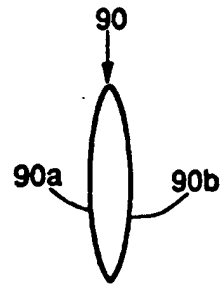


FIG. 10.

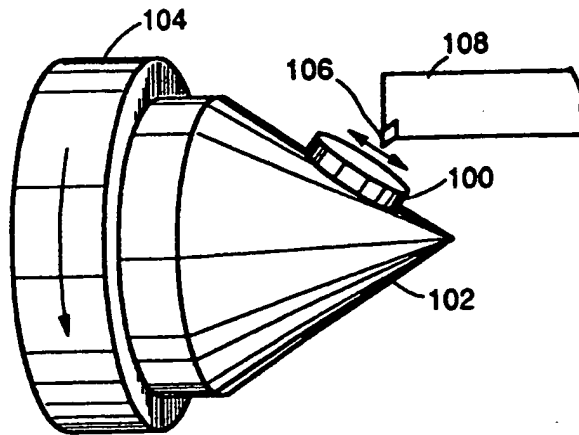


FIG. 11.

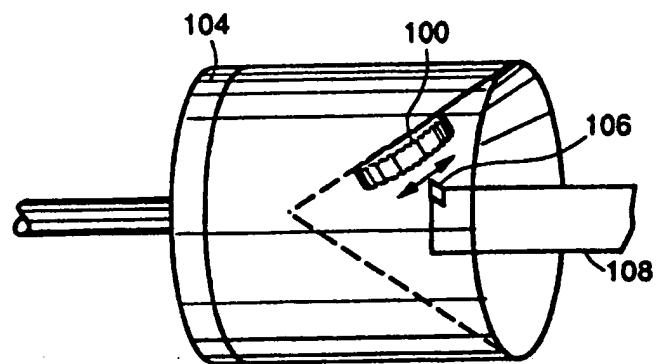


FIG. 12.



European Patent
Office

EUROPEAN SEARCH REPORT

Application Number
EP 94 30 1754

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.5)
X	US-A-4 291 848 (CLARK) * the whole document *	1,4,10	F41G7/22
D,A, P	US-A-5 220 159 (FRIEDENTHAL) * the whole document *	1,4,10	
A	FR-A-2 635 921 (S A T) * abstract * * page 3, line 11 - page 5, line 28; figures 1-4 *	1,4,10	
A	US-A-4 717 822 (BYREN) * abstract * * column 3, line 21 - column 4, line 10; figures 3,4 *	1,4,10	
A	EP-A-0 509 394 (BODENSEEWERK GERÄTE-TECHNIK GMBH) * abstract; figures 1-13 *	1,4,10	
			TECHNICAL FIELDS SEARCHED (Int.Cl.5)
			F41G
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 19 May 1994	Examiner Blondel, F
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